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THE CREEP AND FRACTURE OF LEAD AND LEAD ALLOYS

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE UTILITIES RESEARCH COMMISSION

BY

HERBERT F. MOORE
BERNARD B. BETTY
AND
CURTIS W. DOLLINS

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ENGINEERING EXPERIMENT STATION

PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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UNIVERSITY OF ILLINOIS
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ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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Abstract

In this bulletin there is given a brief résumé of previous work on the creep of lead and lead alloys, the results of which were published as Bulletin No. 243, Engineering Experiment Station, University of Illinois. Further creep tests have been made, and, in place of estimating the resistance to creep from the rate of creep alone, the McVetty method of estimating the total creep in a given time under a given stress and at a given temperature has been developed for lead and lead alloys. This method is fully explained in the bulletin.

A comparison of the average values of creep in one year for four metals (lead, antimony-lead, tin-lead and calcium-lead) is presented. Some creep tests on specimens containing oxide inclusions are reported.

It is pointed out that short-time tests for creep have not so far proven reliable for predicting the creep of lead under low stresses continued for a long time.

A considerable number of tests to fracture of lead and lead alloys under steady load and under repeated cycles of reversed bending have been made. The apparatus for such tests is described, and test results given both for steady load tests and for reversed bending tests. A comparison of the results of tests to failure under these two conditions shows that both produced spreading cracks, but that a *steady* load does not start a crack until fracture is imminent.

Extensive metallographic studies of creep and fracture of lead have been made, and evidences have been obtained of intracrystalline slip under short-time tests, and of rotation of crystalline grains under long-time tests,—at least, of rotation of grains on the surface.

A method of making single-crystal specimens is described, and a few results of creep tests and fracture tests of single-crystal specimens of lead are given.

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CREEP AND FRACTURE OF LEAD AND LEAD ALLOYS

I. Introduction

1. *Introductory.*—About six years ago an investigation of the slow stretching of lead and lead alloys under steady load was begun. This was sponsored by the Utilities Research Commission under the special guidance of the Commonwealth Edison Company, Chicago, Illinois.

The investigation is of special importance in connection with the behavior of the sheathing used to protect electrical cables. Troubles due to creep and fracture of sheathing are more numerous than are dielectric troubles.

In 1932 University of Illinois Engineering Experiment Station Bulletin 243, "The Creep of Lead and Lead Alloys Used for Cable Sheathing," by Moore and Alleman was issued. In that bulletin it was pointed out that the mechanical damage to cable sheathing may be caused (1) by cracking, which may occur due to the bending of the cable after it is put in place, or to repeated stresses caused by temperature changes or by vibrations, or (2) by undue distortion caused by "creep," which is the continuing deformation of a metal under a steady load. Since the publication of that bulletin it has been found that cracks may develop in lead and lead alloys under "creep" due to continued steady loads, but that cracks develop very rarely except when complete fracture is imminent. Creep in lead sheathing is, however, a source of possible damage due to the gradual expansion which may go on in the cable sheathing, and to the possibility that this expansion might reach a point where "voids" occur in the insulation and between the insulation and the sheath of a cable, with resulting insulation troubles. Since the publication of Bulletin 243 a considerable amount of data on creep of lead and lead alloys has been obtained at the University of Illinois, and some work has been done on the failure of lead due to repeated stress. This bulletin presents these additional data, and gives some information about various special tests which have been made.

2. *Acknowledgments.*—At the present time the Utilities Research Commission Advisory Committee for this study comprises:

D. W. Roper, (Chairman), Commonwealth Edison Company
John Chumasero, The Peoples Gas, Light & Coke Company
Herman Halperin, Commonwealth Edison Company

C. A. Jaques, Public Service Company of Northern Illinois
E. O. Schweitzer, Commonwealth Edison Company
K. W. Miller, Director, Utilities Research Commission

Their suggestions and criticisms have been very valuable, and are heartily acknowledged.

The investigation has been sponsored by the Utilities Research Commission, Chicago, Illinois, W. L. Abbott, President. It has been carried on as a part of the work of the Engineering Experiment Station, University of Illinois, and has been under the general administrative direction of Dean M. L. Enger, director of the Engineering Experiment Station, and Prof. F. B. Seely, head of the Department of Theoretical and Applied Mechanics.

Acknowledgment is also made to N. J. Alleman, Special Test Assistant in Engineering Materials, for assistance and suggestions.

II. Tests of the Creep of Lead and Lead Alloys Under Long-Continued Load

3. *Review of Previous Work of Investigation.*—In 1932 the first bulletin dealing with the work of the lead sheathing investigation was published, Bulletin 243 of the Engineering Experiment Station, Uni-

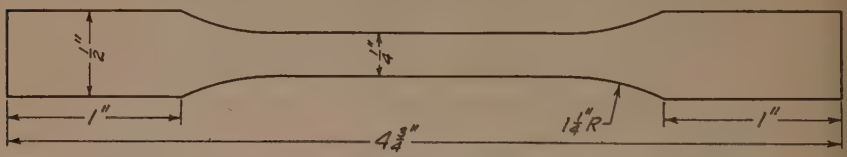

Fig. 1. Test Specimen for Creep Tests and Fracture Tests of Lead and Lead Alloys

versity of Illinois. This bulletin gave the results of a large number of tests of the creep of cable sheathing made of various alloys of lead.

Figure 1 shows the test specimen used for creep tests. Its length was determined by the maximum length which could be cut transversely from the smallest cable sheath furnished. Load was applied directly by dead weights to specimens hung from racks, and Fig. 2 shows such a test rack. Extension was measured over a gage length of 1 inch by means of the apparatus shown in diagram in Fig. 3.

The principle of the strain-measuring apparatus employed for the long-time tension tests is shown in Fig. 3. A pair of clamps fitted with a 10-to-1 lever L grips the specimen S. The change in distance y measures the creep of the metal over any interval of time. The

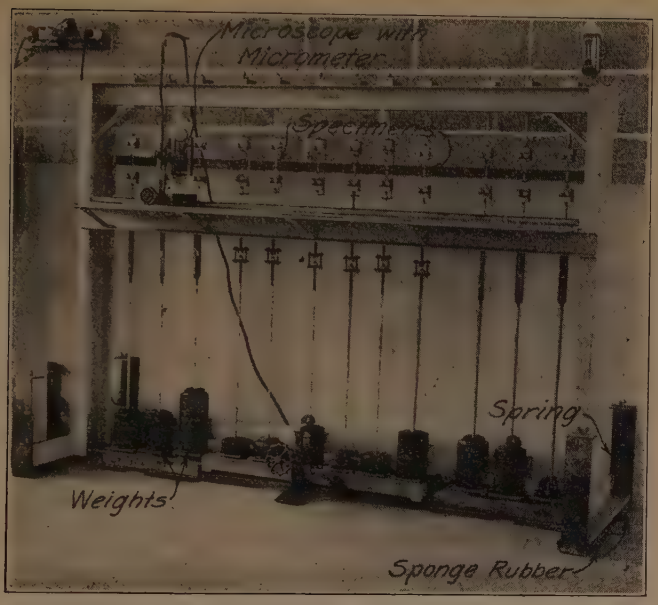

FIG. 2. TEST RACK FOR CREEP TESTS UNDER LONG-CONTINUED STEADY LOAD

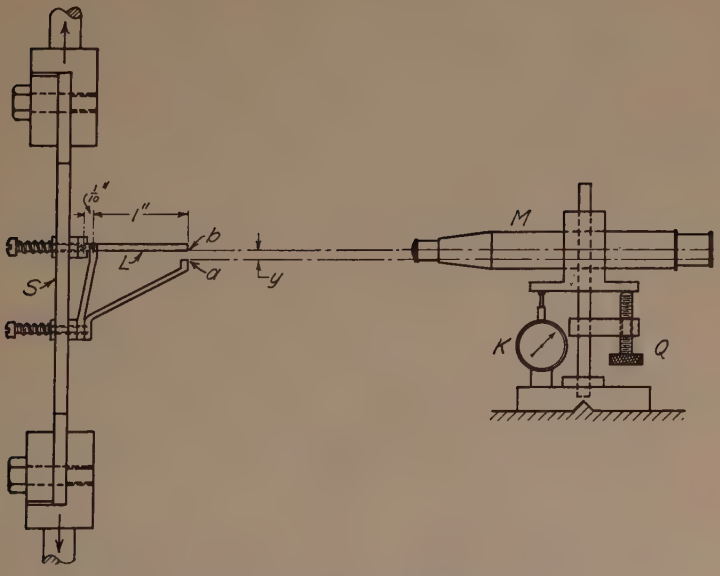

FIG. 3. APPARATUS FOR MEASURING CREEP OF LEAD AND LEAD ALLOYS UNDER STEADY LOAD

distance y is measured at intervals by means of the miscroscope M, which is fitted with cross-hairs. The microscope is moved up and down by means of the screw Q. It is focused at b, a reference mark on the moving arm, and then at a, a reference mark on the frame. The difference in reading between the two positions as shown on the dial micrometer K is noted, and the change in this difference between readings gives the creep which has occurred. The sensitivity of this apparatus is 0.0001 in. A more complete description of the details of the apparatus will be found in Bulletin 243.

The results were given in the form of diagrams showing, for the different alloys tested, the number of hours for 1 per cent creep (reciprocal of rate of creep) for several alloys, under various stresses, and at temperatures of 32 deg. F., room temperature, and 150 deg. F. Data were also presented obtained from the actual expansion of three sheaths under continued hydrostatic pressure. The diagrams of test results not only indicated a diminishing rate of creep with diminishing stress, but seemed to give some indications of a limiting stress below which the rate of creep was either zero, or very minute indeed. A method of determining an arbitrary limiting stress (creep limit) below which the creep rate was very slow was proposed.*

4. *Further Creep Tests and Summary of Creep Data to Date.*— Creep tests of specimens of various lead alloys have been continued since the publication of Bulletin 243, especially long-time tests under low stresses. Quite a few tests have been run continuously for periods

*Since the publication of Bulletin 243 there has appeared a criticism of the results given because no study was made of the aging of the metals tested, and because the test specimens were flattened out from cylindrical sheathing.

With the exception of the calcium-lead alloys, all the metal tested at the University of Illinois had been aged for at least one year before the specimens were placed in the test racks. Of the lots of calcium-lead tested one lot was about a month old when specimens went into the test racks, and the other lot was nearly five months old. Obviously the study of metal from extruded sheathing which had been aged for some time would give more significant results as to service strength and creep than would the study of newly extruded metal.

As to the criticism with respect to flattening out tensile specimens, it may be pointed out that transverse tests seem more important than longitudinal, and that the alternative to using flattened transverse specimens for creep tests is to use cylindrical specimens loaded by hydraulic pressure. With such specimens it is necessary to solder, or otherwise to fasten, pieces of hardened steel, which shall serve as points for micrometer measurements. Now this soldering of material to the surface of a cylindrical specimen diminishes the circumferential length which stretches, and an element of uncertainty is introduced into the measurement of percentage of creep.

Moreover, British experiments by Waterhouse and Willows, reported in Research Reports of the British Non-ferrous Metals Research Association, Association Series No. 287A (Jan. 1932), indicate that, judged by changes in hardness, lead alloys recover very quickly from strain hardening, usually within a day or two. These results are in harmony with hardness tests made at the University of Illinois, and the Illinois experiments included tests on calcium-lead, which was not tested by Waterhouse and Willows. It seems unlikely that any cold work due to the tensile strain of flattening out specimens (about 3 per cent maximum) would seriously affect the results of creep or fracture tests extending over several days or weeks.

Indirect evidence as to the effect of flattening of specimens is given by the comparison of test results from specimens cut longitudinally from a sheath and specimens cut transversely. If there is much effect from flattening specimens the results for the transverse specimens might be expected to differ appreciably from those for longitudinal specimens. No marked difference between results for transverse and for longitudinal specimens was noted.

It is believed that the value of the results reported in Bulletin 243 and in this bulletin is not seriously diminished either by the lack of aging tests or by the use of flattened out specimens.

of two and a half and three years. Creep studies have also been carried out on pure lead with oxide inclusions, on single-crystal specimens of lead, and on several specimens of lead extruded by special process, or treated in some particular manner. Creep tests have also been started on an alloy of cadmium, antimony, and lead, and on an alloy of tellurium and lead.

Unless specifically stated to the contrary data reported in this bulletin are from tests of specimens so cut that welds did not occur within the reduced section.

The long-time tests have all shown distinct creep at the lowest stress used, and, in view of this fact, it seems that a *diagram giving the estimated amount of creep under a given stress for various lengths of time* is a more useful criterion of the behavior of lead and lead alloys than is the arbitrary creep limit proposed in Bulletin 243.

After trying several methods of presenting creep data, the method was chosen which was proposed for creep of ferrous metals by Mr. P. G. McVetty of the Westinghouse Laboratories in his paper, "The Interpretation of Creep Tests" presented before the 1934 meeting of the American Society for Testing Materials.*

This method of interpretation is best understood by a study of typical diagrams such as those shown in Figs. 4, 5, and 6. The data of a creep test are plotted directly as shown in Fig. 4. The creep rate v for any stress is the slope of the straight line part of the creep-time curve.† (Fig. 4). It will be noted that the straight line which gives the rate of creep does *not* pass through the origin of the diagram. Quoting Mr. McVetty, "In other words, its equation must have the form $e = e_0 + vt$ rather than $e = vt$. Any analysis of families of creep curves must make some allowance for the more rapid creep rate in the initial stage."

In this equation, e denotes total creep for any time t, v denotes rate of creep ($\Delta e/\Delta t$ in Fig. 4) and e_0 denotes "initial" creep (as shown at the left hand side of Fig. 4).

In preparing the data of creep tests up to date the original data were in the form of creep–time records similar to those shown in Fig. 4. From data plotted as in Fig. 4 a stress–rate-of-creep diagram for each metal at each temperature can be prepared, similar to that shown in Fig. 5.‡

*Proceedings American Society for Testing Materials, Vol. 34, Pt. II, p. 105, 1934.

†There is some question as to whether this is a straight line or whether the rate of creep diminishes up to the point where fracture begins. However, for all the lead alloys studied a straight line represents this creep-time diagram over the greater portion of the tests very closely indeed.

‡In the actual interpretation of data of tests at Illinois, in place of this stress-rate-of-creep diagram, diagrams with stress plotted against time to creep 1 per cent were used. Many of these diagrams are given in Bulletin 243.

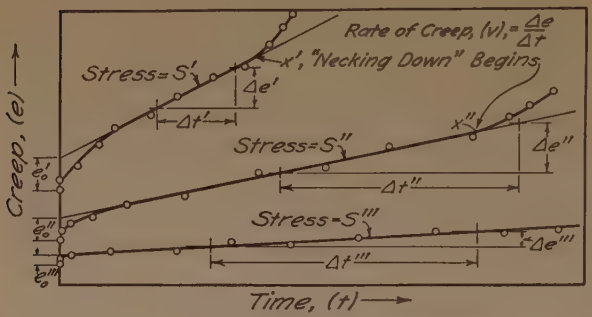

FIG. 4. CREEP–TIME DIAGRAMS

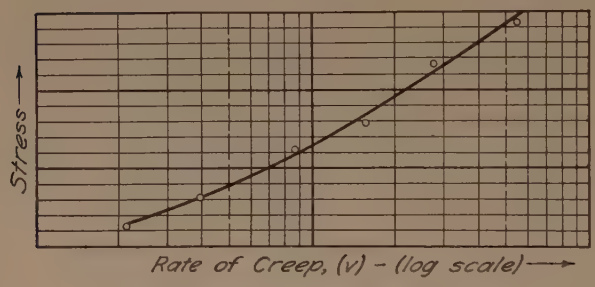

FIG. 5. STRESS–RATE-OF-CREEP DIAGRAM

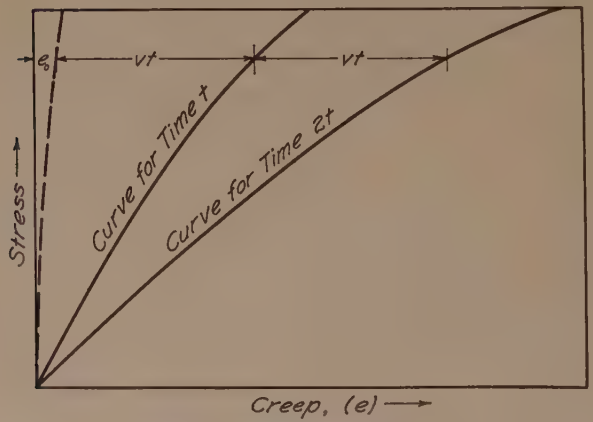

FIG. 6. STRESS–CREEP DIAGRAM

From the stress–rate-of-creep diagram (Fig. 5) a stress–creep diagram can be plotted as shown in Fig. 6. Values of e_o for different stresses are taken from the creep–time diagrams (Fig. 4), and the e_o line drawn as shown by the broken line at the left hand of Fig. 6.

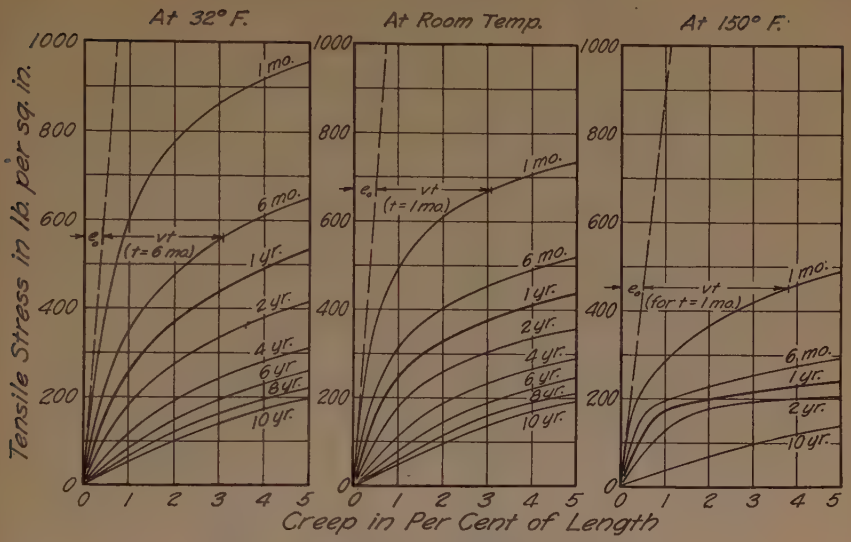

FIG. 7. CREEP OF COMMERCIAL PURE LEAD

Average of test results.

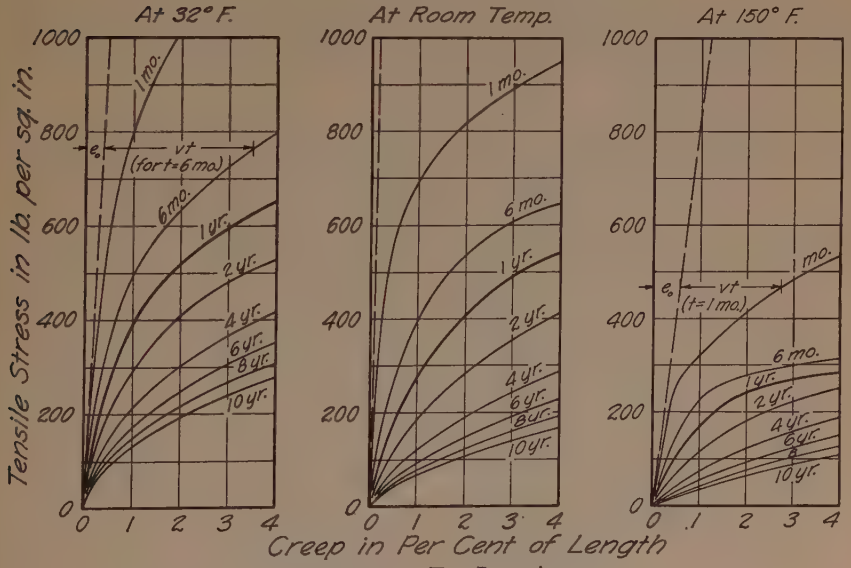

FIG. 8. CREEP OF TIN-LEAD ALLOYS

Average of test results, tin content ranging from 1 to 3 per cent.

For any given stress the rate of creep v is taken from the stress–rate-of-creep diagram, (Fig. 5), then for any given stress S and any given time t the creep is $e_0 + vt$. The creep for time $2t$ is then $e_0 + 2\,vt$. In this way a series of creep diagrams for various times can

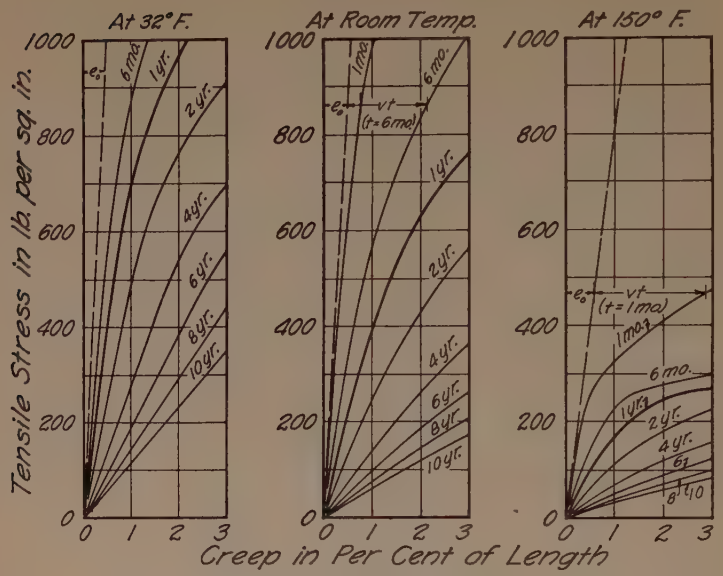

FIG. 9. CREEP OF ANTIMONY-LEAD ALLOYS

Average of test results, antimony content ranging from 0.75 to 1.0 per cent.

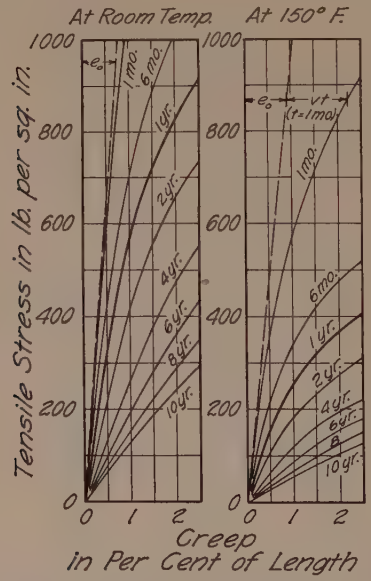

FIG. 10. CREEP OF CALCIUM-LEAD ALLOY

Average of test results, calcium content 0.04 per cent.

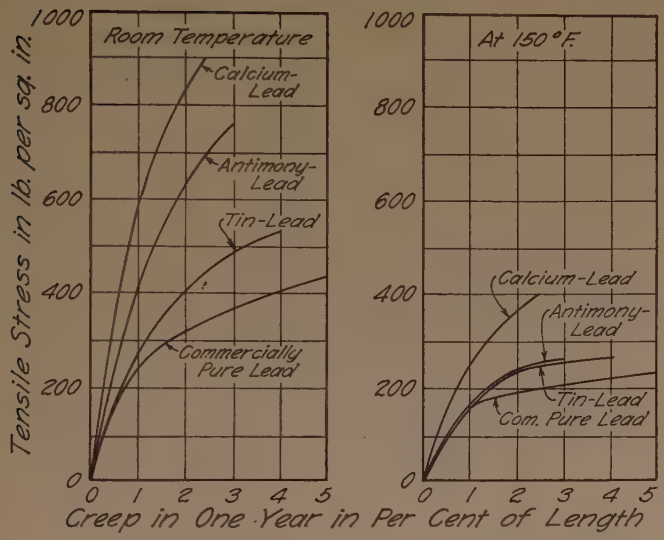

FIG. 11. COMPARATIVE CREEP OF METALS TESTED

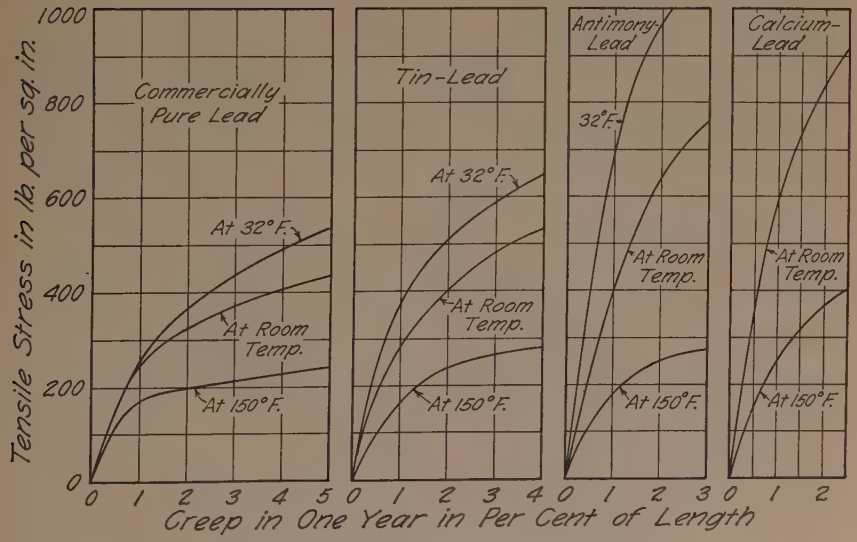

FIG. 12. EFFECT OF TEMPERATURE ON CREEP

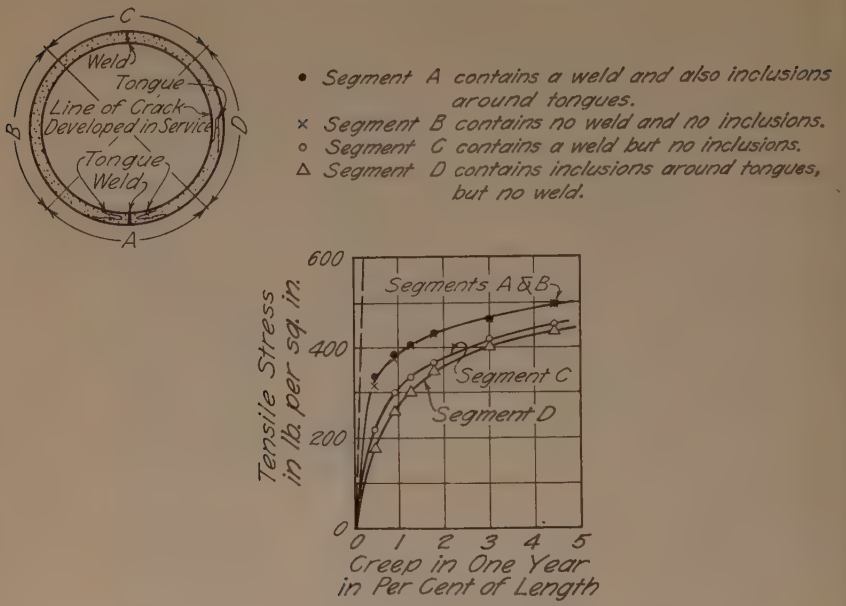

Fig. 13. Creep of Lead Containing Oxide Inclusions

be drawn, and such diagrams for the lead alloys tested to date are shown in Figs. 7 to 13 inclusive.

Using the methods described in the preceding paragraph, the creep for any given time can be computed. However, if the time passes the limit of the beginning of the incipient "necking down," which is preliminary to fracture, (points x' and x'' in Fig. 4), the creep–time diagram will no longer follow a straight line, and the actual creep will be greater than that given by the diagram. By a study of fracture curves, such as are shown in Fig. 15, an estimate of the lowest creep which is likely to correspond with the beginning of necking down has been made, and Figs. 7 to 10, inclusive, show the limits assumed for reliable determination of creep from the diagrams. It will be noted that the limits assumed vary from 2½ per cent for calcium-lead to 5 per cent for commercial pure lead.

The determination of e_0 for various specimens is a matter of some uncertainty. When the earlier tests were made the importance of the initial stretch was not realized, and some inconsistencies in the values for e_0 may be seen. However, the value of e_0 is small compared with the creep and it is not believed that the inconsistencies noticed introduced serious errors into the creep results.

These diagrams show the *average* results for specimens from a number of different sheaths made of the same type of alloys. There was considerable variation in the metal taken from different sheaths, but it is believed that this general average summary will be of use.

Figure 11 gives a comparison of the creep in one year for the different alloys tested, for the room temperature tests, and for the tests at 150 deg. F. Figure 12 shows the comparative creeps of certain alloys at different temperatures.

The effect of the alloying elements antimony and calcium in increasing resistance to creep is obvious, especially at the higher stresses. It is also evident that further tests for creep at low stresses, using more sensitive extensometers, are desirable.

5. *Creep of Specimens Containing Welds and Oxides.*—Figure 13 gives a comparison of the creep of metal in the various segments of a sheath of commercial pure lead, in which there were two well-marked groups of oxide "inclusions" forming "tongues" which extend in a circumferential direction. It is to be noted that one of the segments containing inclusions (Segment D) shows the greatest creep, while the other segment containing inclusions (Segment A) shows about the same creep as a segment without weld and without inclusions.

This rather indecisive result for the tests of creep in lead with inclusions appears to be in harmony with the hypothesis that structural damage by creep in metals is determined by the action of an appreciable volume of metal in the regions of high stress, rather than by actions at minute areas of high localized stress. In this respect it resembles elastic deformation of a structural or machine member, and the effect of slip on static strength. The effect of localized inclusions on the *fracture* of lead is discussed later.

6. *Significance of Creep in Lead Sheathing.*—As will be discussed more fully later in the section on metallographic tests, the danger of developing cracks due to creep in initially-sound lead or lead alloys seems rather slight under service conditions. In metal free from initial cracks and oxide inclusions cracks have been observed only in the last stages of creep, after an amount of distortion which would furnish ample warning, and would probably constitute serious structural damage. If serious distortion does constitute structural damage to a sheath as, for example, might be the case when the increase of volume inside the sheath caused "voids" in the insulation of a cable of the ordinary type, or caused large gaps between the outside of the insulation and the inside of the sheath of a cable of either the oil-filled or

the ordinary type, or caused both these phenomena to occur, then creep would be of marked significance. It may be noted that it is very difficult to detect incipient trouble from creep of sheath in a cable in service. In this connection it may be stated that three test sheaths (of three different alloys) in the University of Illinois laboratory have been under a constant oil pressure of 25 lb. per sq. in. for about three years. During that time the diameters have increased approximately 0.65 per cent, 0.91 per cent and 1.52 per cent respectively, and no cracks have developed.

No absolute limiting stress, below which lead and its alloys do not creep at all, has been found.

The effect of alloying ingredients in slowing up creep at high stresses is very marked. Their effect seems less marked for stresses in the neighborhood of 200 lb. per sq. in. and lower, and further tests with more sensitive strain measurements are necessary before it can be finally determined what the effect of alloying ingredients is at very low stresses.

7. *Unreliability of Short-time Tests for Creep.*—The tests for creep described in the preceding paragraphs are time consuming, and it is natural that attempts should be made to determine creep properties from ordinary tension tests, or very much shorter tests. Unfortunately all such tests of lead so far proposed have failed to prove their reliability for predicting creep of lead and lead alloys. It is frequently assumed that below the "true" elastic limit no creep occurs, and attempts to locate such a "true" elastic limit for metals have been made with much care and with very delicate strain measuring apparatus. It is doubtful if any metal has a "true" elastic limit, very doubtful indeed whether lead alloys do, and quite certain that any of the numerous kinds of elastic limit determined in laboratory tests is unreliable as a measure of creep, or as an index of any "creep limit" below which creep does not occur at all. It is the experience of the University of Illinois laboratory that a creep determination must carry some tests at least 1000 hours before really reliable predictions of creep can be made. Possibly this figure might be somewhat reduced by the use of more sensitive strain-measuring apparatus.

III. Fracture of Lead and Lead Alloys Under Long-Continued Steady Load

8. *Spreading Cracks Under Steady Load.*—The phenomena of slip and creep as revealed by microscopic examination is discussed in a

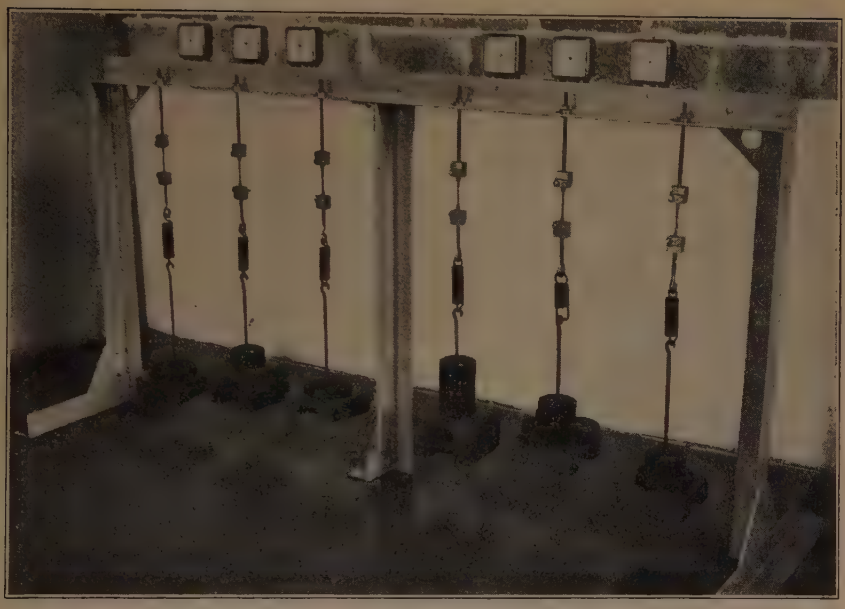

FIG. 14. RACK FOR FRACTURE TESTS OF LEAD AND LEAD ALLOYS UNDER STEADY LOAD

subsequent section of this bulletin. It may be noted here that under long-continued steady load actual cracks in lead and lead alloys tested have not been observed until fracture was imminent, or at least not until the "necking down" stage of creep, as shown in Fig. 4, was reached. However, fracture of lead and lead alloys will take place under long-continued loads which set up stresses far below those required to produce fracture in ordinary testing machine tests. Some study of this phenomenon of fracture has been carried out on a number of kinds of metals.

9. *Test Specimens and Test Apparatus.*—The specimens used are of the same form and size as those used for creep tests. Again it may be noted that this size and shape of specimen was chosen so that transverse specimens could be cut from samples of sheathing.

Figure 14 shows the test rack used for long-continued loading to fracture. To the lower grip of each test specimen is attached a cord, which, when the specimen breaks and the weights drop, pulls out a small piece of wood, releases a pawl and stops a clock placed above the specimen, thus showing the time which has elapsed for failure. The weights are hung from the specimen grips by helical springs to

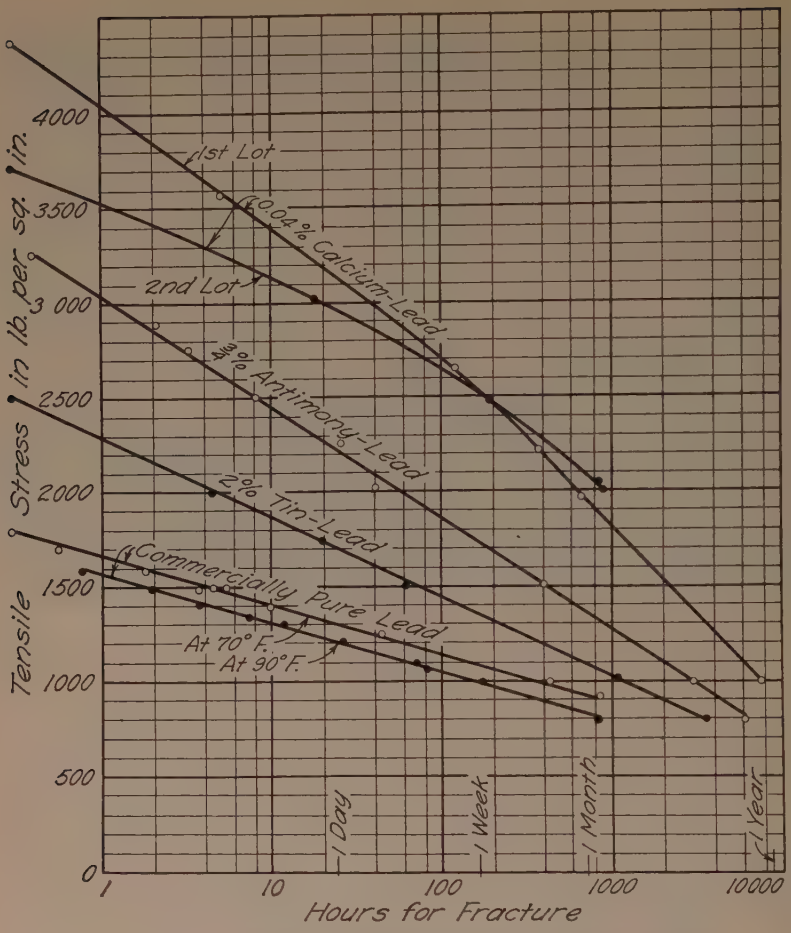

FIG. 15. RESULTS OF FRACTURE TESTS OF LEAD AND LEAD ALLOYS UNDER STEADY LOAD

minimize any shock transmitted through the floor and the frame of the rack when a specimen breaks.

Figure 15 and Table 1 give the results of long-time steady load tests to fracture. In Fig. 15 the ordinates show the stresses (lb. per sq. in.) at which fracture occurred. The abscissas, plotted to a logarithmic scale, show the number of hours required to fracture a specimen. For example, the specimen of antimony-lead which failed at the lowest load fractured under a stress of 800 lb. per sq. in. after having withstood that stress for more than 6000 hours. The values given at the extreme left hand of Fig. 15 are values for tests made in a testing machine with a speed of pulling head of 0.02 inches per minute.

TABLE 1

STRESSES AT FRACTURE AFTER ONE YEAR UNDER STEADY TENSILE LOAD COMPARED WITH ENDURANCE LIMITS FOR 50 000 000 CYCLES OF REVERSED FLEXURE

Metal	Endurance Limit lb. per sq. in.			Stress for Fracture after 1 Year under Steady Tensile Load lb. per sq. in.
	10 000 000 cycles of stress 700 r.p.m.	10 000 000 cycles of stress 2500 r.p.m.	50 000 000 cycles of stress 2500 r.p.m.	
Commercial Pure Lead	700	650	400	650
2 per cent Tin-Lead Alloy	700	980	800	650
0.75 per cent Antimony-Lead Alloy	1200	1300	1000	750
0.04 per cent Calcium-Lead Alloy	1500	1550	1000	950

10. *Test Results.*—From the test results as shown in Fig. 15 two negative conclusions appear to be justified: (1) Ordinary tension tests of lead and lead alloys made in the testing machine yield very little information about the resistance to fracture under long-continued steady load. In any event, the results of a testing machine test of lead are of very little significance unless the approximate rate of strain is given. (2) Tests extending over periods varying from one month to ten months give no sign of any limiting stress below which lead will not fracture under long-continued load. In this respect the results of fracture tests are in line with results of creep tests, and with results of tests under repeated stress, which are discussed in the next chapter. Obviously tests under low stresses acting for a longer time than any test period yet tried are necessary before the existence of any such limiting stress can be established, if, indeed, there is any such limiting stress. In general, Fig. 15 indicates about the same order of merit for the various alloys as was indicated by creep curves for room temperature in Fig. 11. It may be noted that nearly all observed fractures of lead alloys under long-continued loading were intercrystalline. Commercial pure lead "necks down" to a very small section at fracture, and the distortion is so great that it is difficult to determine either the origin or the path of fracture.

Tests to fracture, corresponding to the creep tests previously described, were made on specimens cut from the test sheath containing inclusions. The results of these tests to fracture are given in Fig. 16. It will be noted that the highest resistance to fracture was developed by the specimens cut from Segment D, which contained "tongues" of inclusions, but no weld. The specimens from the other three segments differed but little in resistance to fracture under long-continued steady load, with the specimens from Segment A (which contained both in-

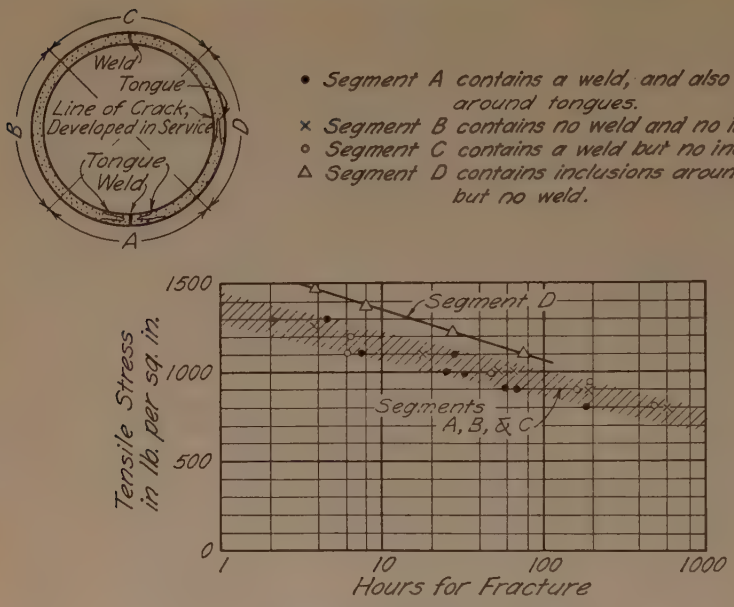

FIG. 16. RESULTS OF FRACTURE TESTS OF LEAD CONTAINING OXIDE INCLUSIONS

clusions and a weld) showing, perhaps, a trifle lower resistance to fracture than those from the other two segments. However, a service fracture had occurred in the sheath in a segment in line with that segment of the test section which contained inclusions and showed the greatest creep.

This result, while obtained from too few tests to be at all conclusive, gives some support to the hypothesis that inclusions which tend to cause minute areas of stress-intensification have very little effect on the resistance to fracture of lead under long-continued *steady* loading. This is analogous to the effect of localized stress on the ordinary static tensile strength of ductile metals, and in sharp contrast to the marked effect which local stress-intensification has in reducing the strength of metals under repeated stress. Repeated stress tests of lead containing inclusions seem to furnish a profitable field for study.

11. *Ductility of Lead and Lead Alloys Under Long-continued Loading.*—In the case of a number of tests of specimens to fracture under long-continued steady load the per cent elongation at fracture was plotted against the logarithm of hours to fracture. The data so

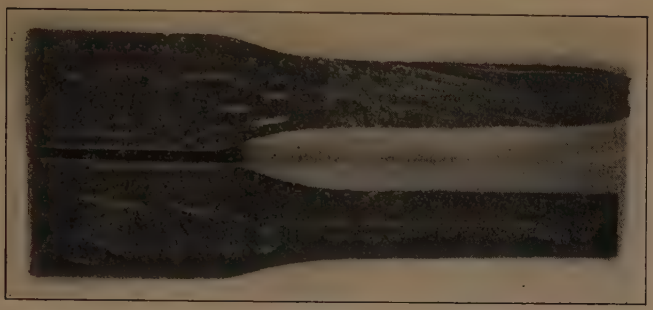

FIG. 17. TWO TYPES OF FRACTURE OF ANTIMONY-LEAD ALLOY
Upper specimen, tensile stress 3000 lb. per sq. in.; fracture after 32 min.
Lower specimen, tensile stress 2000 lb. per sq. in.; fracture after 42 hr.

far obtained are not sufficient as a basis for any quantitative values, but for tin-lead, antimony-lead, and calcium-lead there was shown a distinct tendency for elongation to *diminish* with length of time required for fracture. This tendency is present, although to a less degree, in the tests of plain lead. The question as to whether air corrosion causes this loss of ductility suggests itself as worthy of study.

In the case of tin-lead and antimony-lead there is a distinct difference in character of fracture between specimens pulled quickly and specimens which fractured after a number of hours under steady load. Figure 17 illustrates this difference. No such marked difference in appearance of broken specimens has been observed for commercial pure lead, and the character of fracture of calcium-lead seems distinctly different from that of the other metals both under short-time steady-load tests and under long-time steady-load tests.

IV. FRACTURE OF LEAD AND LEAD ALLOYS UNDER REPEATED CYCLES OF REVERSED BENDING STRESS

12. *Metals Studied.*—In connection with the study of the creep of lead, Mr. C. W. Dollins took as graduate work in the University of Illinois a study of the failure of certain lead alloys under repeated cycles of reversed bending stress. Mr. Dollins studied metal from four pieces of sheathing, (1) commercial pure lead, (2) 0.75 per cent antimony-lead alloy, (3) 2 per cent tin-lead alloy, and (4) 0.04 per cent calcium-lead alloy.*

13. *Specimens and Testing Machine.*—The specimen used for the repeated-stress tests of lead made at the University of Illinois is

*Very extensive tests of fatigue of lead alloys have been made at the Bell Telephone Laboratories in New York City under the general direction of Mr. J. R. Townsend. See Proceedings, American Society for Testing Materials, Vol. 27, Part II, p. 153 (1927); Vol. 29, Part II, p. 353 (1929); Vol. 30, Part II, p. 395 (1930) and Bell Laboratories Record, Vol. XIII, No. 1, p. 12 (Sept. 1934).

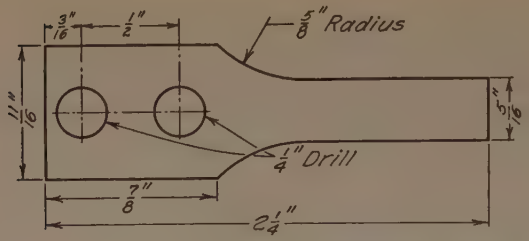

FIG. 18. SPECIMEN FOR FATIGUE (REVERSED FLEXURE) TESTS OF LEAD AND LEAD ALLOYS

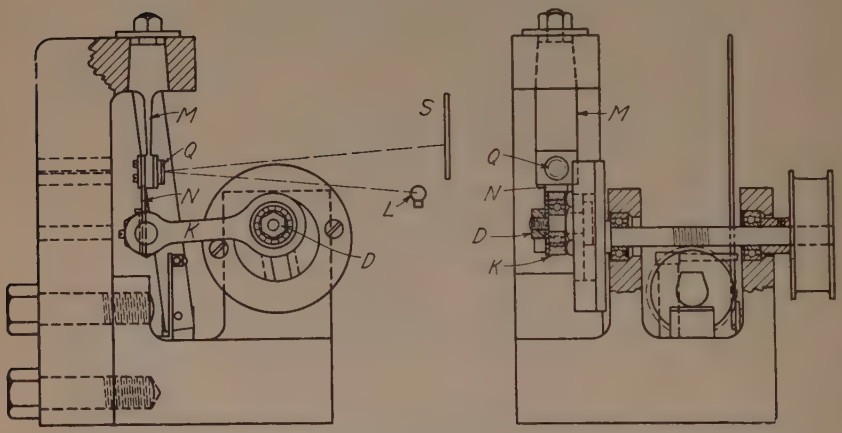

FIG. 19. TESTING MACHINE FOR FATIGUE TESTS OF LEAD AND LEAD ALLOYS

shown in Fig. 18. Each specimen was polished on its flat faces using No. 00 emery cloth as the final polishing material. The direction of rubbing was longitudinal. An exception to this treatment occurred in one series of tests on antimony-lead, in which the specimens were not polished at all.

The testing machine is shown in Fig. 19. The machine applies repeated stress by flexure produced by means of a variable-throw crank and connecting rod, and gives a measure of the stress set up by the deflection of a short flat steel spring.

The specimen N is fastened at one end to the calibrated flat spring M, and the other end of the specimen is vibrated back and forth by the connecting rod K, which is operated by the variable-throw crank D. If the throw of the crank is increased the bending moment and the stress on the specimen are increased, and the deflection of Q (a mirror attached to the calibrated spring) is also increased, causing motion of a beam of light reflected from the lamp L to the screen S.

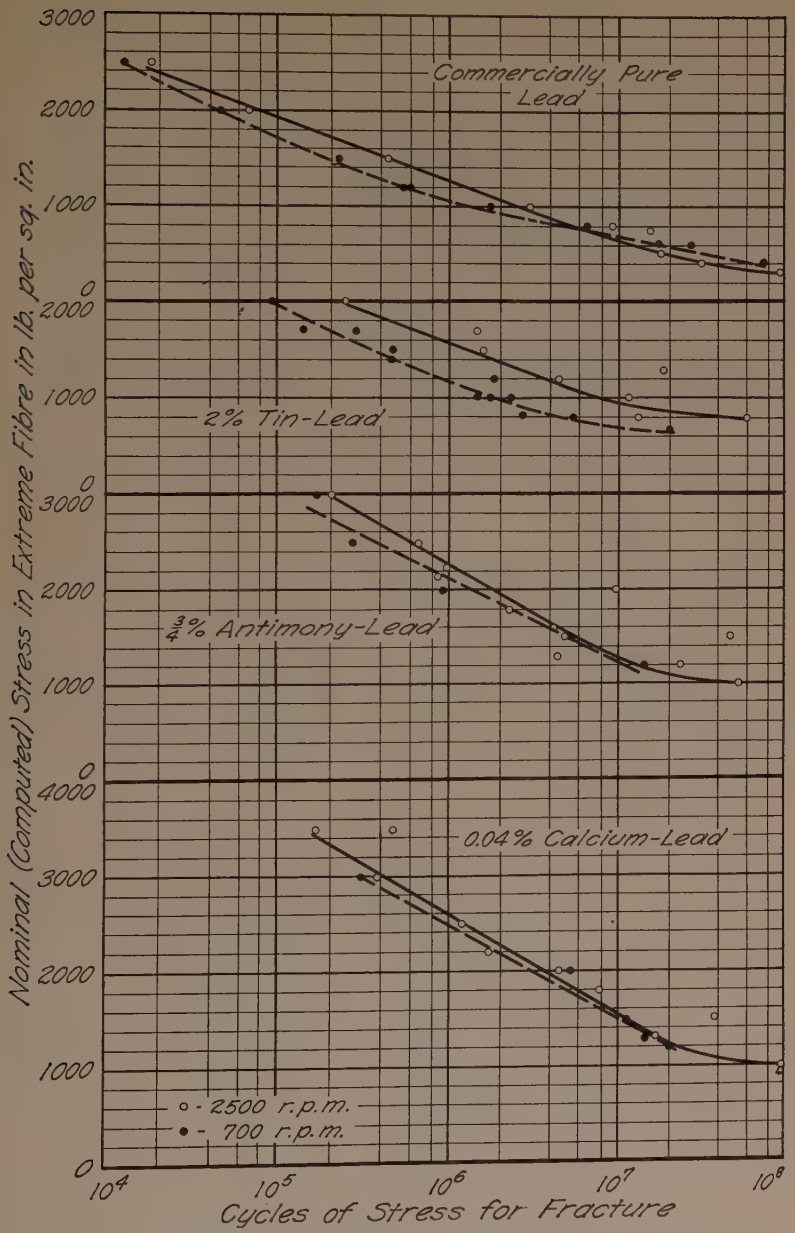

FIG. 20. *S-N* DIAGRAMS FOR FATIGUE TESTS OF LEAD AND LEAD ALLOYS

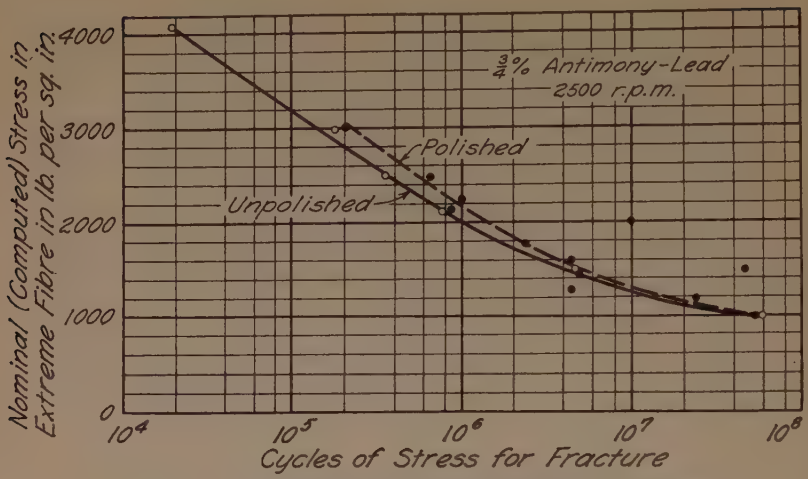

FIG. 21. *S-N* DIAGRAMS FOR FATIGUE TESTS OF POLISHED AND UNPOLISHED ANTIMONY-LEAD ALLOY

The motion of the beam of light along the screen *S* is, then, a measure of the stress in the specimen. There is provided an automatic trip which is operated by the dropping of the connecting rod *K* when the specimen breaks. The falling connecting rod releases a pivoted arm, which falls, opens the motor switch, and stops the machine. A counter is also provided which records the number of revolutions of the machine. The fatigue tests of lead and lead alloys were run at two speeds, 700 r.p.m. and 2500 r.p.m.

14. *Results of Fatigue Tests of Lead and Lead Alloys.*—Figures 20 and 21 show in diagram the data of the tests under repeated cycles of reversed flexure. Such diagrams are commonly known as *S-N* diagrams, and *S-N* diagrams for the ferrous metals and most of the non-ferrous metals become horizontal at some critical stress, locating a limiting stress below which it is assumed that fracture will not occur no matter how many cycles of stress are applied. It will be noted that some tests on lead and lead alloys were carried to 100 000 000 cycles of stress, and that no well-defined endurance limit was shown; the diagrams do not become horizontal. In this respect the results resemble those obtained from fatigue tests of certain aluminum alloys. For purposes of comparison endurance limits have been determined for 10 000 000 cycles of stress and for 50 000 000 cycles of stress. It is believed that these endurance limits will be valuable in giving *comparative* fatigue strengths of the various alloys tested. These results are given in Table 1.

It may be noted that the effect of speed on the results of fatigue tests does not seem to be very great over the range from 700 to 2500 r.p.m.

Figure 21 shows a comparison between the behavior under repeated stress of lead, of antimony-lead specimens polished, and of specimens of the same material unpolished. In this particular case no very marked difference was observed at the lower range of stress, but the polished specimens show slightly longer endurance under the higher stresses.

The values of endurance limit at 50 000 000 cycles of stress as given in Table 1 are distinctly higher than the values reported by Townsend and Greenall.* It is to be noted that Townsend and Greenall used a rotating-beam specimen which required metal at least ½ inch thick, and that it might be expected that this thick material would give somewhat lower values for fatigue strength than the thin metal from which the specimens tested at the University of Illinois were cut.

15. *Comparison of Stresses for Fracture Under Steady Load and Under Cycles of Reversed Bending.*—Table 1 gives not only the endurance limits for various numbers of cycles of stress but also the stress required for fracture after one year for several different alloys. It is again to be noted that no absolute limits have been obtained either for the fracture of lead and lead alloys under repeated stress, or for their failure under long-continued steady tensile load. However, comparing results of tests under steady load with those of tests under repeated load, it is to be noted that for the calcium-lead, the antimony-lead, and the tin-lead alloys, the endurance limit for 50 000 000 cycles of stress was higher than the stress for fracture under long steady load for one year. On the other hand, for commercial pure lead the endurance limit for 50 000 000 cycles of stress was distinctly below the stress for fracture under steady load for one year. This result would seem to give certain indications that, for the three alloys mentioned, the limiting stress under steady load for a few years might be expected to be lower than the endurance limit for 50 000 000 cycles of repeated stress.

If creep plays any part in causing the fracture of lead and lead alloys in service, the *time* during which the metal is under stress will be a factor in the resistance of the metal, as well as the number of cycles of repeated stress to which it is subjected. Furthermore, over long periods of time, the question of corrosion by air and by moisture,

*Proceedings, American Society for Testing Materials, Vol. 30, Part II, p. 395 (1930).

and its effect on fracture, may have to be considered. The results of repeated-stress tests at 700 cycles per minute and of tests at 2500 cycles per minute showed very little difference, but the difference in time required for the tests amounted, at most, to only 10 days, or 240 hours. Preliminary tests have been made under cycles of stress applied once per minute, but these tests will be extremely time-consuming, and results from them are not yet available.

It may be noted that if time were the *only* factor affecting the fracture of lead, tests under steady load might be expected to give lower strength values than tests under repeated stress, in which the maximum stress is applied for only a portion of the time which elapses during the test.

At the present time there is considerable experimental evidence that a spreading fracture in lead or lead alloys may develop under either long-continued steady load, or under cycles of repeated stress, but *no limiting stress has been found* for either type of stress below which fracture will not eventually occur.

Figure 22 is a micrograph of the intercrystalline fatigue fracture of an antimony-lead alloy.

V. Metallographic Study of Creep in Lead and Lead Alloys

16. *Distortion of Lead and Lead Alloys Under Load.*—At the present time the distortion of lead and its alloys under load may be classed as either (1) slip under heavy stress, or (2) a continuous slow creep. Further metallurgical study may show these two phenomena to be very closely related, but at present they may best be considered separately. Figure 23 shows a micrograph of lead which has been permanently stretched by a load applied in a few minutes by a testing machine. The structure of the lead is seen to be made up of crystalline grains, and across many of these grains may be seen "slip lines" indicating a sliding of layers of metal within the crystal something like the sliding of the cards in a pack. Such slip is characteristic of ordinary plastic flow of metals.

Figure 24 shows the appearance of three lead alloys at various intervals after each has been subjected to tensile stress. The micrograph to the left shows the appearance just before being subjected to load (except for the antimony-lead). The surface is seen to be marked by the scratches of the sharp knife used to cut the specimen to shape, and no outline of crystalline grains is visible, as the specimen was not etched to bring out the grain boundaries. After a considerable time

under steady load the same area of the specimen was photographed again, and the appearance was that shown in the center micrographs of Fig. 24. Grain boundaries are quite plainly visible, and a careful examination shows some evidence that some crystalline grains have been rotated slightly, as is shown by the distortion of the scratches. This is shown more distinctly in Fig. 25. Attention is called to the absence of slip lines in these micrographs. Furthermore, in this metallographic study of polycrystalline lead and lead alloys subjected to creep by long-continued steady loads, no slip lines have been observed. The micrographs at the right hand of Fig. 24 show still further distortion of the grains, with apparent widening of the grain boundaries, probably due to shadows cast over the minute ridges raised by grain rotation. If the load is left on until fracture is imminent, cracks open between the grains. Figure 26 shows such a crack in a specimen of lead alloy near to fracture under a steady load. So far in laboratory tests such cracks have not developed under *steady load* until fracture is imminent. On examining the brittle fractures it was found that these cracks were both more prominent and more numerous on those sides of the specimens which had been part of the surface of the extruded sheaths.

A commonly-accepted metallurgical theory of the difference between slip and creep is as follows: Whenever a metal is subjected to stress sufficiently great to cause plastic flow there is a tendency to cause a hardening of the metal, probably by disarrangement of the pattern of arrangement of atoms near the planes of slip. There is also a tendency for the atoms to seek new regular arrangements, which would counteract the hardening tendency, and this "healing" tendency increases with increase of temperature and the resulting increased atomic activity. For steel, and most of the stronger metals, the critical temperature at which the hardening tendency and the healing tendency are equal is well above ordinary room temperature, and no appreciable continuing creep occurs at room temperature. However, for some of the softer metals, notably zinc, lead, and lead alloys, this critical temperature is below ordinary room temperature, and if plastic flow starts creep continues as long as the load is applied. However, it is quite possible that much of the creep which takes place occurs on slip planes within the crystalline grains, and that under steady load the continuing sliding motion is spread over a very large number of planes, and that the motion on any one plane is rarely sufficient to cause a "slip line" to be visible through the microscope. This is discussed further in the section on tests of single-crystal specimens.

As suggested by the micrographs in Figs. 24 and 25, creep seems to cause most marked disturbance at the grain boundaries, and as the length of grain boundaries in fine-grained metal is relatively greater than in coarse-grained metal there seems to be some reason for the opinion that for resistance to creep large grain size is of some advantage.

17. *Development of Cracks Under Steady Load.*—Figure 26 is a micrograph of a crack which was developed in a calcium-lead alloy under a steady load. It was found very difficult to obtain micrographs of cracks before they had spread to final fracture, so rapid was the spread once a real crack started. Such evidence as is available seems to indicate that failure develops as an intercrystalline crack somewhat similar to that shown in Fig. 22 for failure under repeated stress. This very difficulty of photographing a spreading crack in the comparatively short time between its appearance and complete fracture of the specimen emphasizes the fact that under steady load cracks are not likely to develop until fracture is imminent, and the danger of such cracks developing from creep before other evidence of danger has appeared, in the form of extreme distortion, is rather slight. However, at least one case of development of cracks from creep has been reported from practice, and while danger from this source seems slight it can hardly be said to be negligible.

In this connection it may be noted that after about three years continuing creep under a tensile stress of about 200 lb. per sq. in. none of the three full-sized sheaths under internal oil pressure have shown any signs of cracks.

VI. Creep of Single Crystals of Commercial Pure Lead

18. *Purpose of Single-crystal Tests.* — Tests of single-crystal specimens have thrown much light on the mechanism of failure of metals under repeated stress (fatigue), and it seems decidedly worth while to study the creep of single-crystal specimens. It has been seen in Fig. 25 that the mechanism of creep of lead and lead alloys includes movement at the grain boundaries of the lead, at least on the surface. It seems inconceivable that such movement can take place unless there is within the crystals considerable distortion, quite possibly along slip planes. To investigate this point creep tests of single crystals of lead seemed worth while, since in such specimens distortion at the boundaries would be eliminated.

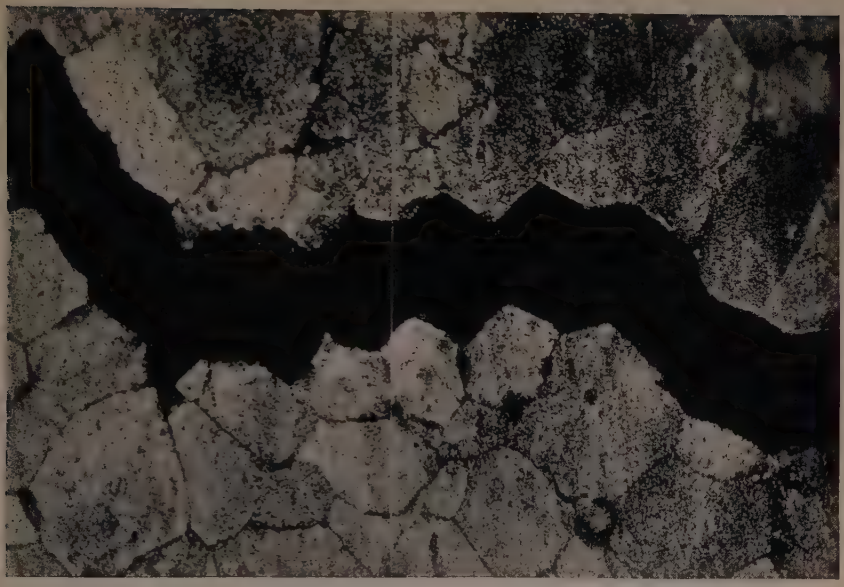

FIG. 22. FATIGUE FRACTURE IN ANTIMONY-LEAD ALLOY
Magnification, 100 X. Etched in hydrogen peroxide and acetic acid.

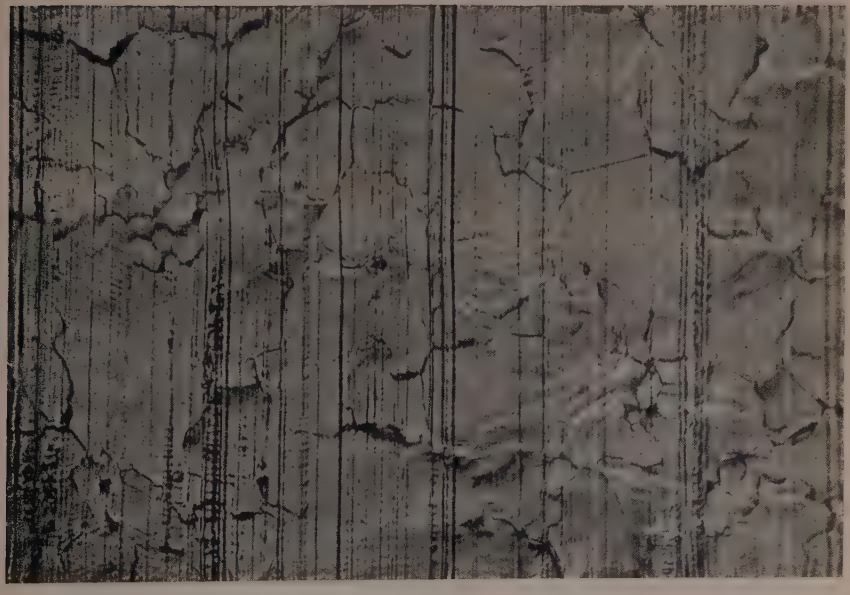

FIG. 23. MICROGRAPH OF LEAD STRETCHED IN SHORT-TIME TENSILE TEST
Note numerous slip lines across grains. Magnification, 100 X.

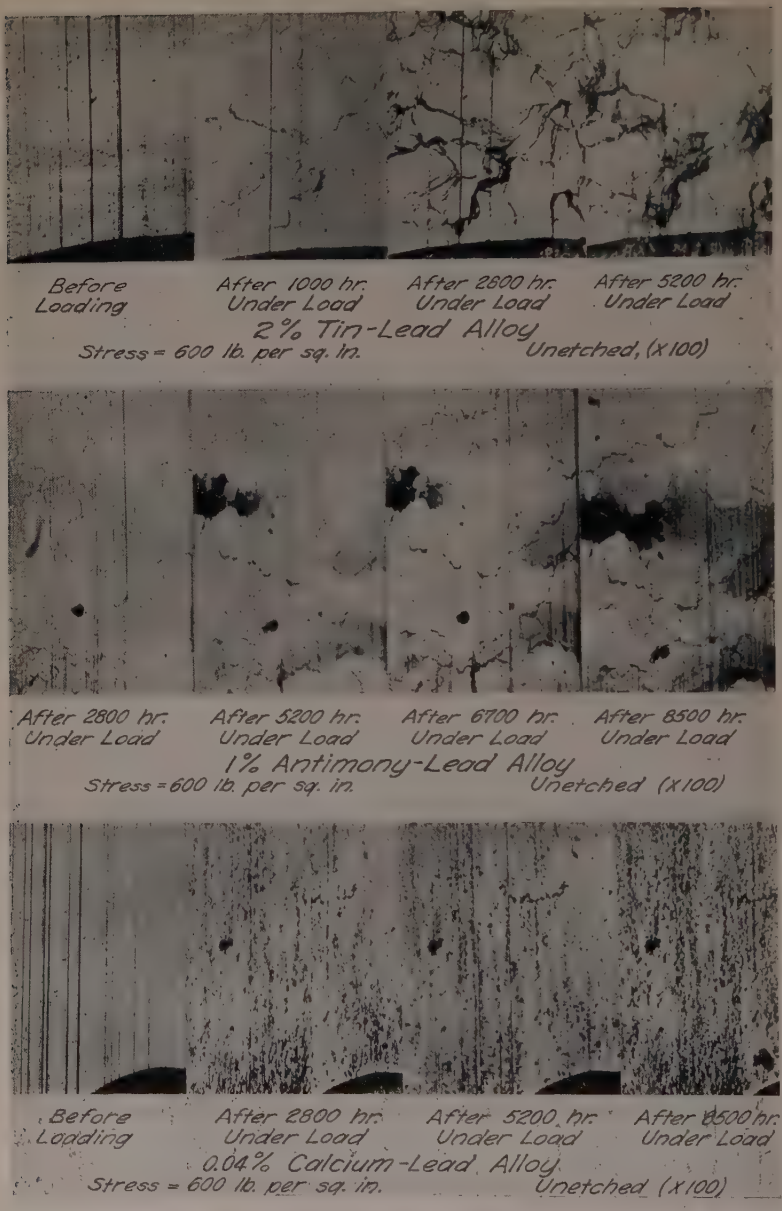
Before Loading
After 1000 hr. Under Load
After 2800 hr. Under Load
After 5200 hr. Under Load
2% Tin-Lead Alloy
Stress = 600 lb. per sq. in.
Unetched, (x100)
After 2800 hr. Under Load
After 5200 hr. Under Load
After 6700 hr. Under Load
After 8500 hr. Under Load
1% Antimony-Lead Alloy
Stress = 600 lb. per sq. in.
Unetched (x100)
Before Loading
After 2800 hr. Under Load
After 5200 hr. Under Load
After 8500 hr. Under Load
0.04% Calcium-Lead Alloy
Stress = 600 lb. per sq. in.
Unetched (x100)

FIG. 24. MICROGRAPHS OF LEAD ALLOYS UNDER LONG-TIME STEADY LOAD TESTS

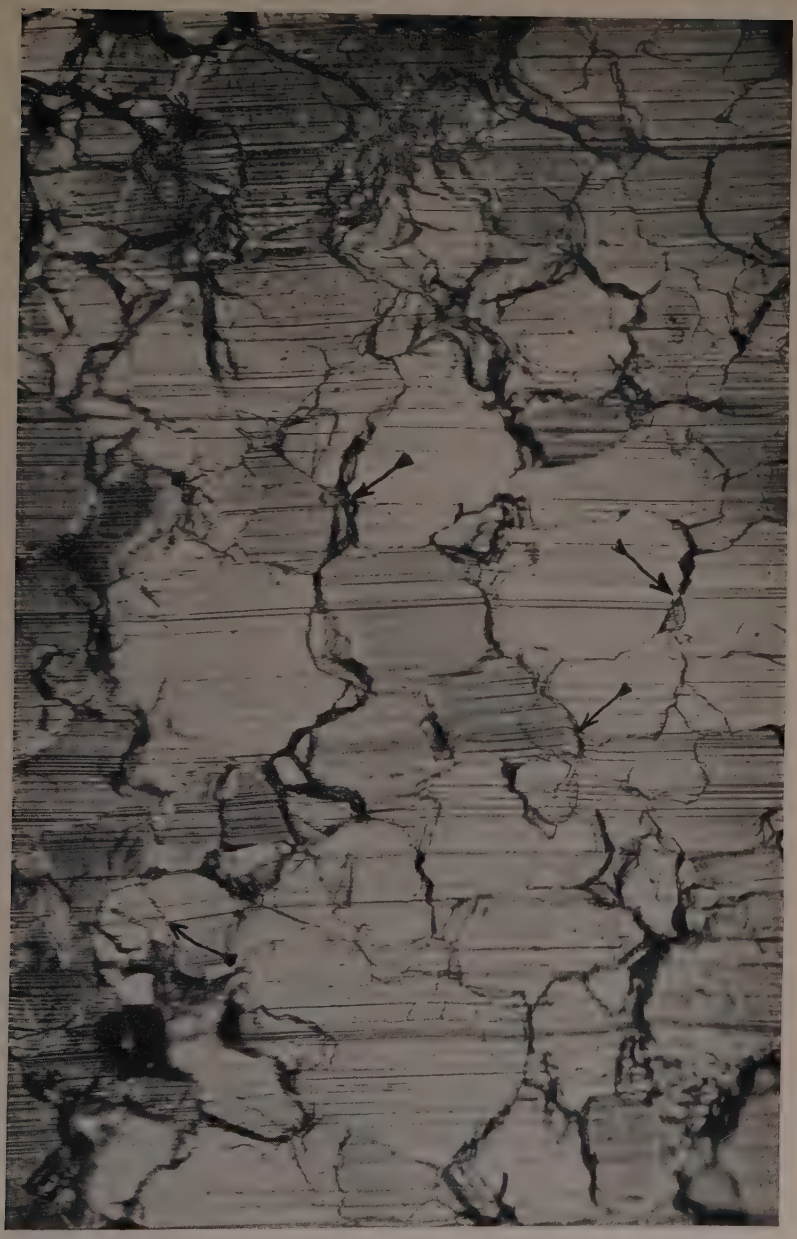

FIG. 25. MICROGRAPH OF 2-PER-CENT TIN-LEAD ALLOY AFTER 1100 HOURS UNDER STEADY TENSILE STRESS OF 1000 LB. PER SQ. IN.

Note the rotation of grains shown by the change in direction of the scratches left by the microtome knife as it cut the specimen; this is especially noticeable at points indicated by arrows. What seem like cracks at grain boundaries are shadows of raised edges of grains. Magnification, 350 X.

FIG. 26. CRACK IN CALCIUM-LEAD SPECIMEN SHORTLY BEFORE FRACTURE UNDER STEADY LOAD

Steady tensile stress of 1000 lb. per sq. in. applied for 2200 hr. Magnification, 400 X.

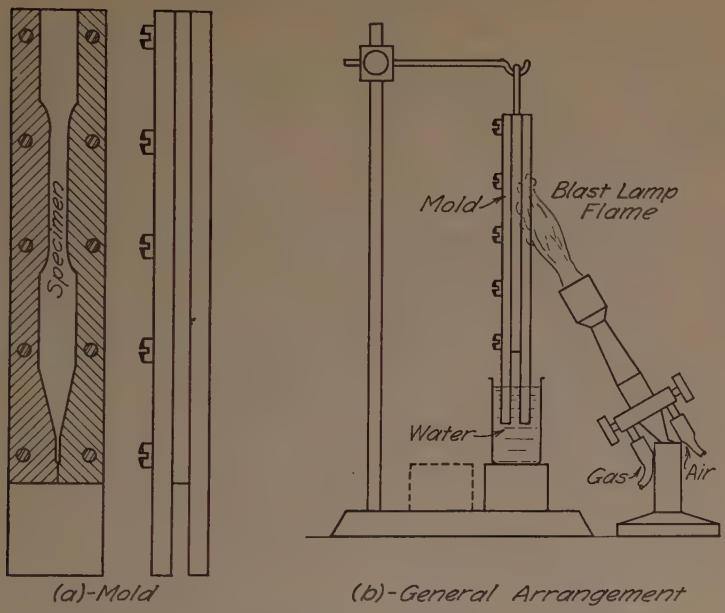

FIG. 27. APPARATUS AND MOLD FOR MAKING SINGLE-CRYSTAL SPECIMENS OF LEAD

19. *Method of Making Single-crystal Specimens.*—The specimens were made in the shape of the specimens used for creep tests, except that the single-crystal specimens had a projecting point at one end. Each specimen was cast in a duralumin mold which could be taken apart for the removal of the casting. This mold is shown in Fig. 27 (a). The specimen was made in this shape so that it would not be necessary to machine or cut it in any way after it was cast, since such cutting might destroy the perfection of the single-crystal structure.

In casting a specimen the lead was melted in a ladle and poured into the assembled mold which had been preheated to the temperature of the molten metal. A temperature gradient was then established along the mold by heating the top with the blast flame and cooling the lower end by occasionally raising the beaker of water, until the projecting flanges of the large mold plates were immersed about one-half inch (see Fig. 27 (b)). While maintaining this gradient all temperatures were decreased gradually by turning down the blast flame so that the lead in the pointed tip at the bottom of the mold was the first to freeze. As the freezing proceeded from the bottom upward molten metal flowed from the top downward to make up for the rather large shrinkage. The progress of solidification was known from this

easily-observed shrinkage in the lead at the top of the mold. Just before solidification was complete the low flame was extinguished and the whole allowed to cool to about 125 deg. F. in the air. The mold was then disassembled and the very ductile specimen carefully removed.

20. *Determination of Atomic Orientation of Single-crystal Specimen.*—In order to determine whether or not the specimen is a single crystal throughout the reduced section it is then immersed in a test tube containing a dilute etching solution — four parts nitric acid (1.72 sp. gr.), three parts acetic acid, and sixteen parts water. Within one or two seconds the surface of the casting, being extremely sensitive to the etchant, shows preferred directional reflecting power for different crystalline grains viewed by ordinary light. By thus examining each face of the specimen the success or failure of the attempt to obtain a single crystal specimen can be seen at once. If a single crystal has been produced over the gage length of the specimen the direction of reflection from the surface of the specimen will be the same all along the gage length. At the time of writing this technique has been developed to such a degree that about one attempt in ten produces a single-crystal specimen.

The method used to determine the crystallographic orientation with respect to the center line and faces of the specimen is essentially that long used by mineralogists in identifying minerals. It was adapted for this purpose by P. W. Bridgman* and slightly further modified by the authors of this bulletin. A rubber ball three and a half inches in diameter of almost perfect spherical shape had a small rod passed centrally through it to which was attached a small brass grip, as shown in Fig. 28. The specimen whose orientation was to be detremined was held in the grip in such manner that its long axis was along the axis of the rod extended. Thus the specimen was co-axial with the sphere. Two great circles were then drawn (1) the equatorial circle perpendicular to the axis of ball and specimen, and (2) the 90-270 degree longitude circle whose plane passed through the axis of the sphere and was parallel to the plane of the large face of the specimen. One of the two points of tangency, on the sphere, of planes parallel to this second great circle was then the point of zero longitude on the equator. These circles having been drawn, the device was taken to a partially darkened room with a single lamp on the ceiling, and was held at arms length toward the floor immediately under the lamp, as shown in

*Physical Properties of Single Crystals of W., Sb., Bi., Te., Cd., Zn., and Sn. American Academy of Arts and Science, Vol. 60, p. 305. 1925.

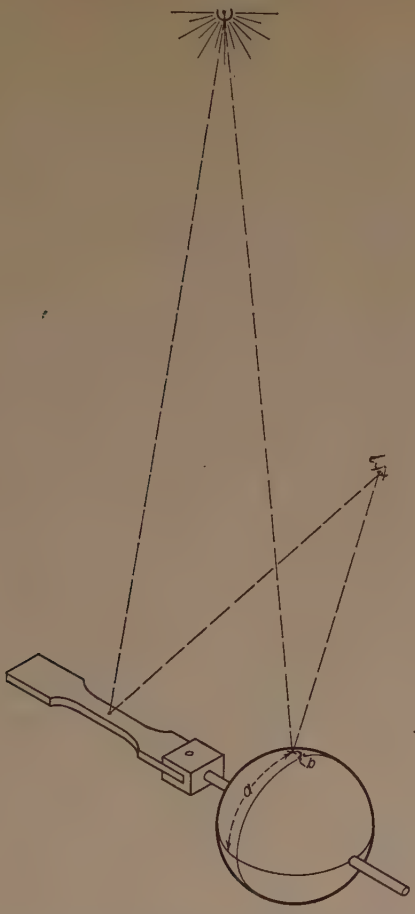

FIG. 28. DEVICE FOR DETERMINING CRYSTALLOGRAPHIC ORIENTATION OF SPECIMEN

Fig. 28. It was rotated until a flash of light, constituting a regular reflection from the myriads of tiny facets on the surface of the crystal was observed. While the assemblage was being held in this position, that point on the polished surface of the sphere at which the image of the lamp overhead could be seen, was marked. This point on the sphere was the point of tangency of a plane which was approximately parallel to the tiny facets reflecting the light from the surface of the crystal. By further rotating and spotting points on the sphere it was found that eight reflections were possible. These eight reflections (four pairs) correspond to the four sets of octahedral planes, planes of maxi-

TABLE 2
CREEP TEST RESULTS FOR SINGLE-CRYSTAL SPECIMENS

Single-crystal Specimen	Load lb.	Octahedral Plane*	Normal Stress lb. per sq. in.	Resolved Shearing Stress lb. per sq. in.	Rate of Creep per cent per hour	Remarks
A	9.5	(111)	119	147	Less than 0.000018	No creep detected in 984 hours.
		($\bar{1}11$)	140	152		
		($\bar{1}1\bar{1}$)	101	142		
		($11\bar{1}$)	99	142		
	16.0	(111)	201	248	0.00036	No slip lines were visible after 4661 hours at this load
		($\bar{1}11$)	235	256		
		($\bar{1}1\bar{1}$)	170	240		
		($11\bar{1}$)	165	239		
B	13.0	(111)	132	194	Less than 0.00002	No creep detected in 506 hours
		($\bar{1}11$)	338	164		
		($\bar{1}1\bar{1}$)	73	160		
		($11\bar{1}$)	2	32		
	16.5	(111)	165	241	Less than 0.0000063	No creep detected in 1625 hours
		($\bar{1}11$)	422	205		
		($\bar{1}1\bar{1}$)	92	200		
		($11\bar{1}$)	3	40		
	22.8	(111)	231	339	0.0025	Slip lines visible on (111) plane. 4661 hours at this load.
		($\bar{1}11$)	592	287		
		($\bar{1}1\bar{1}$)	128	280		
		($11\bar{1}$)	3	57		
C	11.2	(111)	202	142	Less than 0.00002	No creep detected in 480 hours
		($\bar{1}11$)	108	146		
		($\bar{1}1\bar{1}$)	109	147		
		($11\bar{1}$)	88	137		
	18.8	(111)	337	237	Less than 0.000028	No creep detected in 358 hours
		($\bar{1}11$)	180	243		
		($\bar{1}1\bar{1}$)	182	246		
		($11\bar{1}$)	146	229		
	22.2	(111)	400	282	0.000038	Slip lines visible on ($\bar{1}1\bar{1}$) plane. 1850 hours at this load
		($\bar{1}11$)	214	289		
		($\bar{1}1\bar{1}$)	216	292		
		($11\bar{1}$)	173	272		

*The notation for octahedral planes is explained in the Appendix.

mum atomic density, of maximum reflecting power, and the only planes on which slip will occur. A detailed explanation of the notation for and the location of the octahedral plane is found in the Appendix. By taking the average of the latitudes and longitudes (in degrees) of each pair of points the error due to angularity of light balances out and quite reliable results can be obtained. It is now a problem in spherical trigonometry to determine the traces on the faces of the specimen made by each of these sets of octahedral planes. By means of descriptive geometry (or by analytical methods) one can find the

angle between the center line of the specimen and each of these planes, as well as the true area of each intersection. With this information at hand, and the load applied to a specimen being known, one can readily calculate the normal stress and resolved shearing stresses on these planes. Since it had been found by other investigators that, in ordinary plastic deformation of single crystals of face-centered cubic lattice, slip occurred only on the octahedral planes, it seemed reasonable to examine the test specimens in that light.*

21. *Results of Creep Tests on Single-crystal Specimens.* — Creep tests have been made on three single-crystal specimens which may be designated as crystals A, B, and C.

The results of these tests are shown in Table 2, which gives the loading schedules, the resolved shearing stresses on the octahedral planes, and the rates of creep under each loading condition.† Figure 29 shows graphically some of the results of the test.

On removal from the test racks the specimens were carefully examined under a microscope. Crystal A, in which quite an appreciable amount of creep had occurred, showed no visible slip lines on its surfaces. On the other hand, crystals B and C each had a set of well-defined slip lines on each of their respective faces. By determining the orientation of planes whose traces on the specimen were represented by the slip lines the planes on which slip took place in these two crystals were definitely identified as octahedral planes. Furthermore, they were those octahedral planes on which the resolved shearing stress was a maximum.

Slip lines were much broader on the specimen B in which the greatest amount of creep took place. From a study of Table 2 it will be noted that for cases in which the maximum resolved shearing stress was less than about 250 lb. per sq. in. no measurable creep took place, and that for all cases for which the stress was greater than this approximate value creep did take place.

In connection with the absence of slip lines on crystal A it may be noted that its surface was not well suited for observation of such lines. The surface originally was "as cast" and had been subjected to atmospheric corrosion in the laboratory for eleven months. On the other hand the gliding might have been so distributed over several sets of planes that visible slip lines were never produced. Further experiments are expected to throw more light on this mechanism.

*Gough, H. J., "Crystalline Structure in Relation to Failure of Metals," Proceedings, American Society for Testing Materials, Vol. 33, Part II, pp. 20-38 (1933).

†A specimen was subjected to a given stress for a time, and then the stress was increased, as is shown in Table 2.

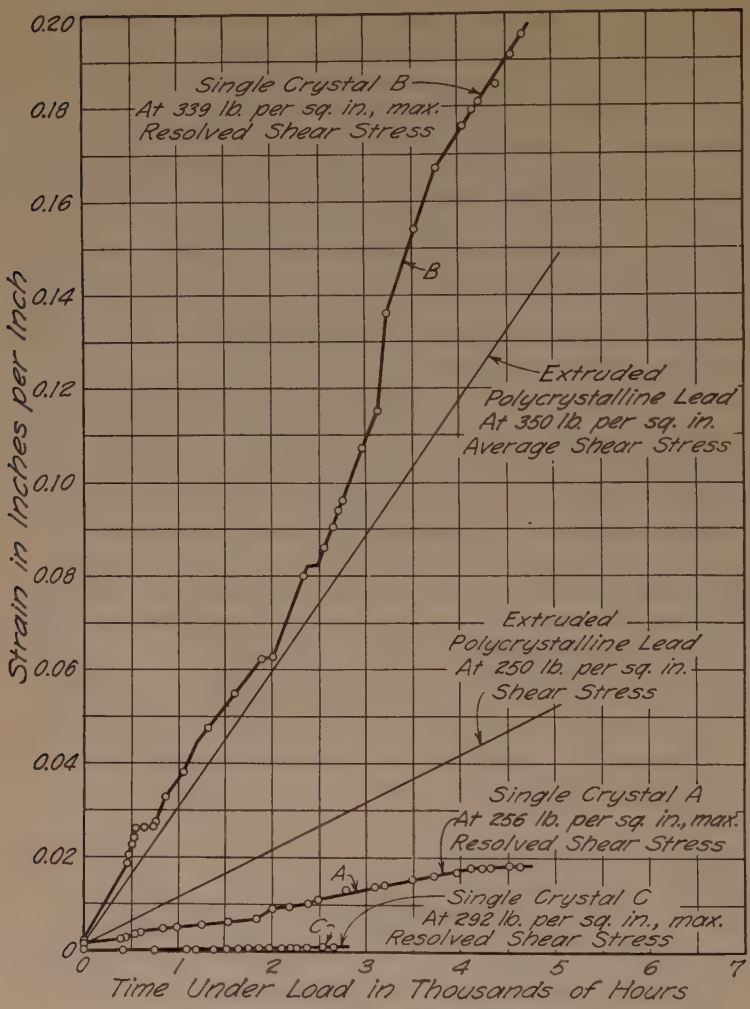

FIG. 29. CREEP OF SINGLE-CRYSTAL SPECIMENS OF LEAD

In the metallographic study of the mechanism of creep of polycrystalline lead cable sheathing, made under conditions well suited for the observation of slip lines, no such lines have been observed under true creep conditions. Figures 24 and 25 do show, however, a marked crystal rotation, at least at the surface.

Whether due to the rotation of grains or to the very slow rate of distortion, it seems that long-time tests may produce a fairly uniform distribution of slide on very many atomic planes. Thus an insufficient

amount of slide occurs on any one plane to cause visible slip lines on the surfaces of the grains.

VII. Conclusions

22. *Summary of Conclusions.* — The following summary of conclusions is given:

(1) No absolute limiting tensile stress has been found for lead or for any lead alloy tested, below which *no* creep occurs. At a stress of 180 lb. per sq. in. and at room temperature creep took place at a rate varying from an average of 0.3 per cent per year for calcium-lead alloy to 0.6 per cent per year for commercial pure lead. At 150 deg. F. the rate of creep under 180 lb. per sq. in. varied from an average of 0.6 per cent per year for calcium-lead alloy to 1.4 per cent per year for commercial pure lead.

(2) On the basis of tests of 1000 hours or more the approximate creep at room temperature under one year of steady tensile stress was determined as follows, for the various metals tested:

Tensile Stress lb. per sq. in.	Creep—per cent of length per year			
	Com'l Pure Lead	Tin-Lead	Antimony-Lead	Calcium-Lead
200	0.7	0.6	0.4	0.3
300	1.6	1.1	0.7	0.4
400	3.9	1.9	1.0	0.6
500 Above	5.0	3.2	1.4	0.8

(3) The superior creep-resisting properties of the alloys of lead tested (as compared with those of pure lead) are greatest at relatively high stresses,—stresses above those commonly met with in practice.

(4) So far there has been found no method of interpreting the results of ordinary testing machine tests of lead and lead alloys, or of interpreting the results of any short-time tests of creep under relatively high tensile stress, so as to predict accurately the creep of the metal under low stresses acting for a long time.

(5) No absolute limiting stress has been found for lead or for any lead alloy tested below which fracture will not eventually occur under steady tensile stress. The following tabulated statement shows the lowest stresses under which fractures were observed for various specimens, the time required for fracture, and the tensile strength developed

in tests in a testing machine with a speed of pulling head of 0.02 inches per minute:

Metal	Tensile Strength in Testing Machine Test lb. per sq. in.	Lowest Stress Under Which Fracture Occurred Under Long-continued Load lb. per sq. in.	Time Required for Fracture Under Steady Tensile Stress
Com'l Pure Lead	1800	600	1 month 5 days
2 per cent Tin-Lead	2500	600	4 months 26 days
0.75 per cent Antimony-Lead	3300	600	8 months 18 days
0.04 per cent Calcium-Lead	4200	1000	10 months 13 days

(6) So far there has been found no method of interpreting the results of ordinary testing machine tests to fracture of lead and lead alloys so as to predict accurately the length of time the metal will withstand steady load without cracking or fracture.

(7) While no limiting stress has been found below which lead and lead alloys will not finally crack under long-continued load, cracking arising from creep of good metal does not appear to be a very serious danger, since creep continues almost to complete fracture before cracking occurs.

(8) Specimens from one sheath were cut from four segments, two of which contained inclusions and two of which were free from inclusions. The specimens from one segment containing inclusions showed distinctly greater creep than did the specimens from the segments free from inclusions; the specimens from the second segment containing inclusions showed about the same creep as did the specimens from the segments free from inclusions. Tests to fracture showed no clearly-marked difference between specimens from segments containing inclusions and specimens from segments free from inclusions. However, it should be noted that a service fracture of the sheath had occurred in line with the segment containing inclusions and showing the greatest creep.

Further tests of metal with inclusions are desirable, especially tests under repeated or reversed stress (fatigue tests), since cable sheaths in service are subjected to variations of internal pressure, and also to some repeated bending incidental to cable movement.

(9) No absolute limiting stress has been found for lead or for any lead alloy tested below which fracture will not eventually occur under cycles of repeated stress. However, below about 200 lb. per sq. in. reversed flexural stress, some 100 000 000 cycles of stress were found necessary to cause fracture for the weakest metal tested. Data

so far obtained are not sufficient to determine the relative length of "life" of lead and lead alloys under long-continued steady load and under cycles of repeated stress. At ordinary room temperatures either long-continued steady load or cycles of reversed flexure may cause failure by a spreading crack.

(10) Microscopic examination of lead and lead alloys subjected to long-continued steady load give evidence of distortion by rotation of grains, at least at the surface. Under short-time tests there are evidences of distortion on account of slip within the grains. It seems possible that under long-continued load the rotation of grains tends to inhibit the development of any very great slip on any one atomic plane, and to favor the formation of many planes of slip, with so slight slip on any one plane that no evidence of slip is visible under the miscroscope.

(11) There seems to be some evidence that lead and lead alloys with large crystalline grains resist creep somewhat better than do lead and lead alloys with small grains.

(12) Creep tests of single crystals of lead indicate that within the crystal distortion takes place along certain definite atomic planes, as has been observed to be the case for many other metals. There seems to be some indication of a limiting resolved shearing stress along these planes below which creep is very slow indeed, and above which it occurs rather rapidly. It must be noted, however, that creep in multicrystalline specimens has been evident at stresses below the limiting values found for single crystals.

Appendix

Crystallographic Notation and Location of Octahedral Planes

Crystals of lead have their atoms arranged in the face-centered cubic system, which means that the unit pattern of atoms is outlined by a cube with an atom at each corner, and one at the center of each of the six faces. For the purpose of this discussion, this pattern may be considered to be repeated indefinitely in all directions. A corner of one of these unit cubes is considered as the origin of coördinates for the three rectangular axes of a three-dimensional system. Let the length of edge of the unit cube be taken as the unit of length for measuring distances along the coördinate axes.

In order to describe the location of the crystallographic planes which pass through and are spoken of as "containing" the various members of any layer of atoms, a system of notation known as the

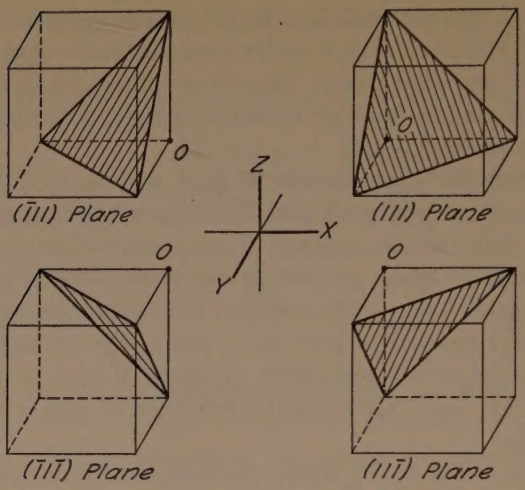

FIG. 30. THE FOUR OCTAHEDRAL PLANES LISTED IN TABLE 2

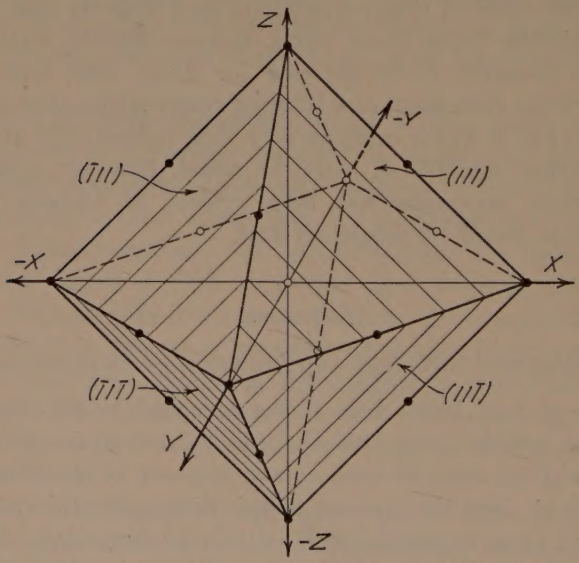

FIG. 31. A CRYSTALLOGRAPHIC OCTAHEDRON OF THE FACE-CENTERED CUBIC LATTICE

Miller indices is used. A plane is located and its direction designated by the reciprocals of its intercepts on the X, Y, and Z axes, taken in that order. Negative values of reciprocal of intercept are denoted by a bar above the number representing the reciprocal of a particular in-

tercept. Figure 30 illustrates the use of the Miller indices in connection with the location of the octahedral planes listed in Table 2.

The atom at the origin of coördinates is shared by eight unit cubes which meet at that point. In each of these cubes there is a plane which has equal intercepts on the axes (disregarding algebraic sign of intercept). These eight planes, then, constitute an octahedron, and for this reason are known as octahedral planes. Figure 31 shows such an octahedron for the face-centered lattice. The octahedral planes are the planes on which the atomic density is a maximum and between which the perpendicular distance is also a maximum. They are the only crystallographic planes along which slip has been observed in the metals with a face-centered cubic lattice.